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FOCAL PLANE ARRAY-BASED MILLIMETER WAVE IMAGING RADIOMETER

Lockheed Martin Corporation

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APPROVED:

DAVID D. FERRIS
Project Engineer

FOR THE COMMANDER:

JOSEPH CAMERA, Chief
Information & Intelligence Exploitation Division
Information Directorate

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Lee Mirth

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Lockheed Martin Corporation
Missiles and Fire Control – Orlando
5600 Sand Lake Road
Orlando, FL 32819-8907

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AFRL Project Engineer: David D. Ferris, IFEA, 315-330-4408, ferrisd@rl.af.mil

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This is an effort resulting from Broad Agency Announcement (BAA) 99-04-IFKPA, Through the Wall Surveillance and Concealed Weapons Detection, dated 8 June 1999. The objective of the effort is to redesign a Concealed Weapons Detection (CWD) brassboard system developed under a previous effort (F30602-95-C-0272) and deliver an upgraded CWD brassboard system designed to provide greater sensitivity and operational reliability.

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FOREWORD

Lockheed Martin Missiles and Fire Control – Orlando submits this Focal Plane Array-Based Millimeter Wave Imaging Radiometer Final Technical Report to the U.S. Air Force Research Laboratory, Directorate of Contracting, in accordance with Contract No. F30602-01-C-0155, Contract Data Requirements List Sequence No. A005.

1.0 INTRODUCTION AND SUMMARY

The Focal Plane Array-Based Millimeter Wave Imaging Radiometer program was structured to provide an upgrade to the brassboard developed under the Concealed Weapons Detection (CWD) Technology program (Contract F30602-95-C-0272). The National Institute of Justice provided $386,819 to fund this program. The contract was administered through the Air Force Research Laboratory (AFRL), Rome, NY. The Program Manager is David Ferris of AFRL.

The brassboard system consists of a line scanning W-Band radiometer, Cassegrain optics with scanning secondary, signal conditioning electronics, and imaging software running on a Pentium III processor. A commercial off-the-shelf (COTS) infrared (IR) camera is available to augment recognition in dark situations.

Real-time images are generated with frame rates of 5 to 30 Hz for normal outdoor subjects with provisions for slower operation under adverse conditions. The brassboard upgrade dealt with improving detector sensitivity, stability, electronics design, scanner enhancement and image presentation. A digital database was generated.

The AFRL final technical report for contract F30602-95-C-0272, report number AFRL-IF-RS-TR-2002-204, documents Phase 1, proof of concept, and Phase 2, brassboard development, and includes examples of images produced and hardware descriptions. Those not familiar with passive millimeter wave technology should refer to that report.

This contract was successful in improving the system operation and enhancing the ability to detect concealed objects under clothing and behind drywall. Detector stability was significantly improved with the use of new MMIC PIN switches. Detector sensitivity was somewhat improved due to partial replacement of the low noise amplifiers (LNAs) with parts having lower noise figure but the full impact was masked by loses introduced by module rework. The scanner was stabilized to give more consistent images. A simple algorithm was used with the improved system operation to provide handgun detection and tracking. A database was collected to document typical system performance and is submitted as CDRL A004.

1.1 Background

The prior contract established the feasibility of concealed weapons detection using millimeter wave radiometers and built a brassboard for operation in real time. Detectors were fabricated using the best MMIC LNA chips available at the time. The brassboard system provided detection of objects concealed under clothing with sufficient sensitivity under clear sky conditions but was unstable due to mechanical and electronic problems and had no provision for the recording of a digital database. The objective of this contract was to upgrade and deliver the exiting concealed weapons detection system brassboard to provide greater sensitivity and operational reliability.

Figure 1.1-1 shows the brassboard system that is configured to operate with a standard PC as a control and display device. The millimeter wave (MMW) camera is contained in a 16 by 16 by 32-inch dust cover and is shown mounted on a cart for portability. The nose cone is a space reserved for any future boresighted video or IR camera. A MMW absorbing shroud (not shown) is provided for the optics to guard against stray radiation.

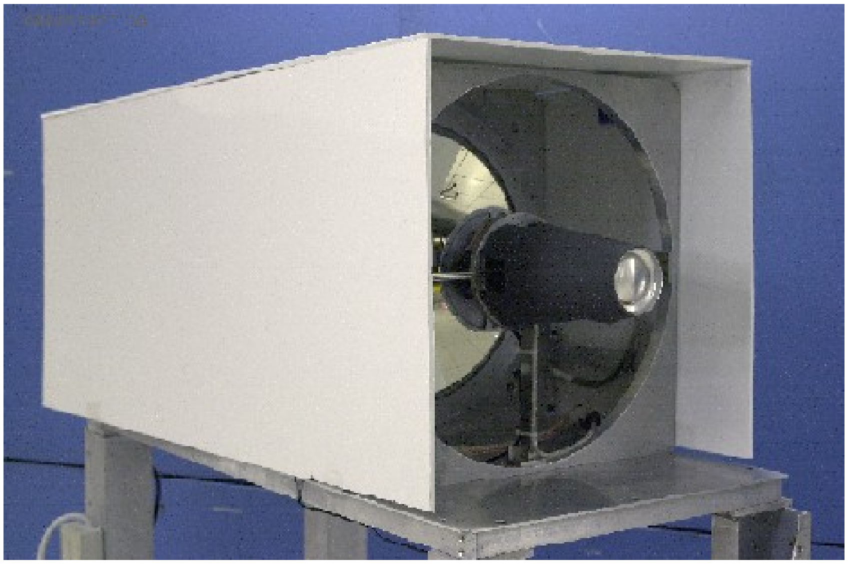

Figure 1.1-1. Passive millimeter wave camera with temporary cover

1.2 Scope

The scope of this effort was to extend the capability of the weapons detection system brassboard through redesign and improvements to take advantage of components not previously available. Replacement and modified components were integrated into the existing brassboard to provide increased functionality and utility. The upgraded system provides effective concealed weapons detection during outdoor operation. Indoor operation is improved and has utility for laboratory experiments. Improved system stability allows operation without the frequent operator attention that was characteristic of the original brassboard system.

2.0 SYSTEM REDESIGN

Design of the brassboard system was reviewed to determine an approach to increase the overall system performance with emphasis on sensitivity and frame rate. The detectors that amplify the extremely low-level radiation by approximately 55 dB to drive a millimeter wave diode initially determine the millimeter wave radiometer sensitivity. Multiple factors can reduce the detectors ability to distinguish small radiation differences. Mechanically, the optic system must be aligned to collect the available radiation and shielded to reduce spurious radiation. Smooth operation of a well-aligned secondary scanning mirror is critical in presenting the image to the aperture of the detector array so that each scene pixel being measured corresponds to the correct pixel location in the image.

A Dickie switch circuit that must have a stable reference and be properly synchronized compensates noise introduced by the LNA gate. The analysis determined that the original MMIC chips used for the Dickie function were unstable due to manufacturing defects that allowed intermittent shorting between metalizations. This caused incorrect operation of the Dickie function since the reference did not appear constant whenever the shorts defeated the design isolation between the scene input and the calibration load. The secondary scanner had several sources of instability: worn bearings, linkage binding and an impractical piezoelectric driven offset mechanism. Circuitry that reads the square wave output from the detector modules was redesigned to provide better calibration and better control over the integration time.

2.1 MMIC Replacements

The Dickie switch MMIC is a custom PIN design not available as a commercial item. M/A-COM was contracted to improve the design and to provide a wafer run. Lockheed Martin Missiles and Fire Control–Orlando (LMMFC-O) provided the specification and W-Band testing of both test structures and final circuits since the vendor did not have W-Band test capability. Specification compliant circuits were produced on the first pass and the yield was more than ample. Detector modules were selected for rework based on measured lack of stability and sensitivity. The switch and the first amplifier were removed and replaced. Figure 2.1-1 shows the new PIN switch bonded in place. In operation, the diodes are biased to alternately connect the output to the scene input and an internal restive load. The square wave drive is normally set to 10 kHz.

The PIN switch was also redesigned to reduce insertion loss that was approximately 2.7 dB in the original switch. The specifications met were:

Frequency	90 to 100 GHz
Insertion Loss	< 2 dB
Isolation	>15 dB
Return Loss	>10 dB

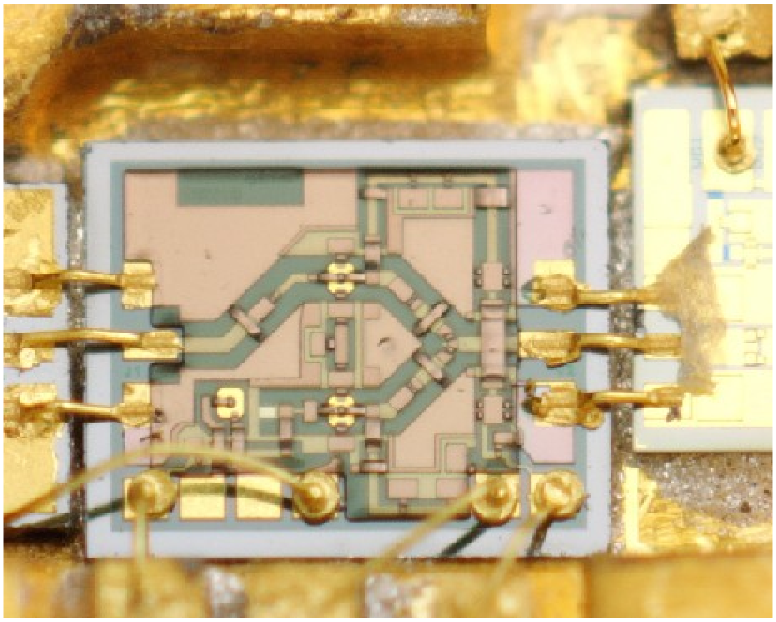

Figure 2.1-1. The Dickie function is performed by a PIN switch MMIC

Low noise amplifiers were more difficult to obtain since the cost of ordering a wafer run was well beyond the funding available. Consequently, the program manager solicited chips from parts on hand at Trex Enterprises. These MMICs were originally produced by HRL Laboratories using the Indium Phosphide process and have noise figures of approximately 3.5 dB with 18 dB gain over our 90 to 100 GHz band. Funding limitations prevented the purchase of sufficient chips to perform a complete LNA replacement so the emphasis was placed on replacement of the first of four cascaded amplifiers since that was the primary determinate of noise figure.

Both replacement chips were somewhat shorter than the original chips resulting in a discontinuity after the first stage of amplification as shown in Figure 2.1-2. On the worst modules a small length of line was added in the gap to reduce the loss.

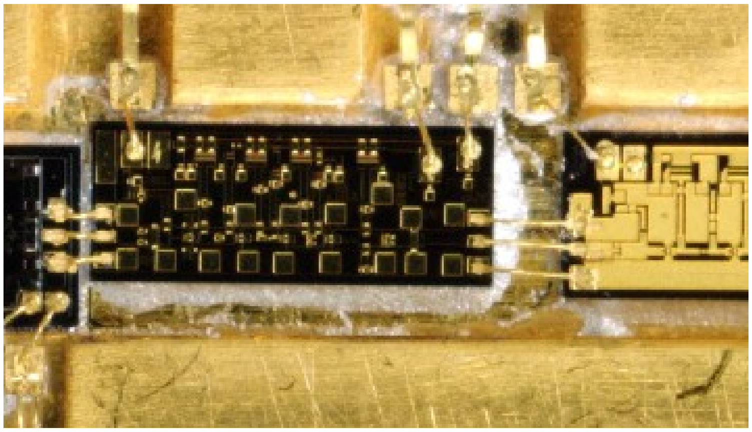

Figure 2.1-2. A gap following the first LNA results in high loss

Another complication arose when replacing the positively biased GaAs LNA with a negatively biased InP LNA. Figure 2.1-3 shows the jumper installed in the reworked modules to supply the new bias voltage.

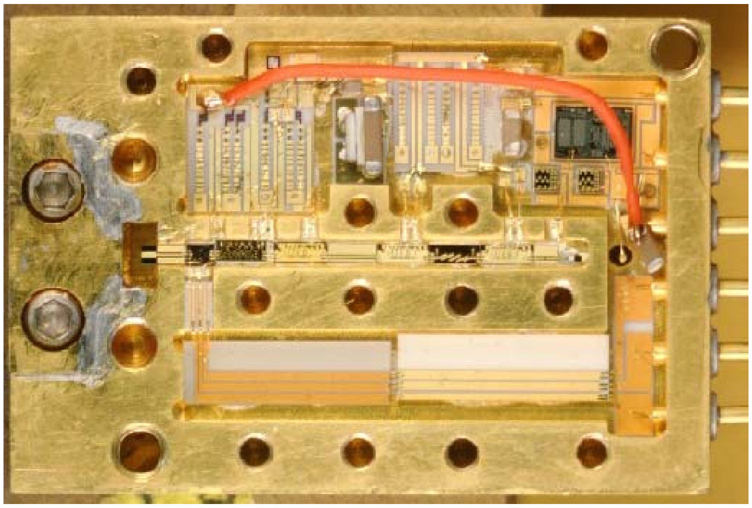

Figure 2.1-3. Bias circuit is jumpered to a previously unused pin

MMIC replacement was successful in increasing the stability of the modules and in providing more uniform sensitivity as shown in Figure 2.1-4.

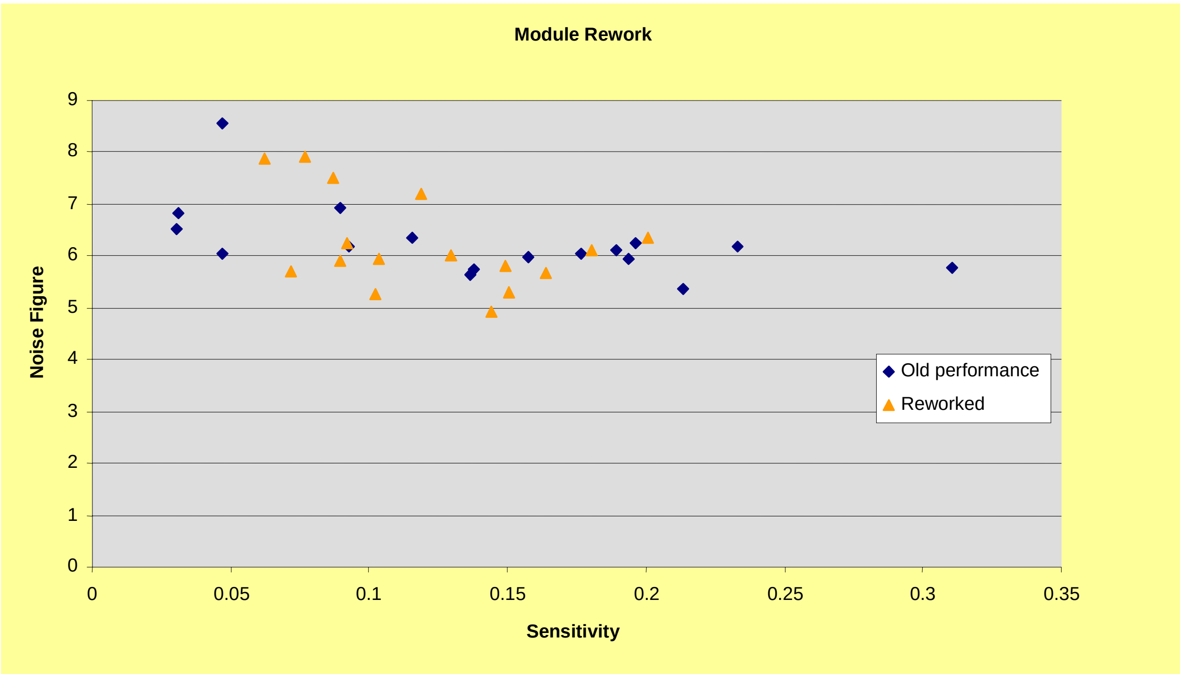

Figure 2.1-4. Reworked detector modules display superior uniformity

When installed in the brassboard the reworked modules exhibited better performance in large part due to the stability that allows the calibration to be set and maintained over several hours of operation in contrast to the previous situation where calibration would be lost within 15 minutes.

2.2 Scanner Modification

The system operation requires the secondary mirror of the Cassegrain optics to perform a narrow rectangular scan to sweep the image over two 1 by 17 arrays of MMW horns (see Figure 2.5-2) at the entrance to the detector manifold. This was implemented with a small motor linked to the mirror to provide vertical scanning and a piezoelectric device to offset the mirror horizontally every half cycle so as to move the image over one half wavelength at the focal plane. This system design provided for Nyquist sampling using horns spaced at one wavelength. Problems arose from the tight coupling of the vertical scan linkage and the mirror mass that loaded the motor and caused irregular motion and from the near-zero tolerance for wear in the horizontal displacement mechanism.

The latter problem was not determined to be correctable without a complete redesign so the horizontal displacement function was simply disabled. Since our calculated blur circle is approximately one wavelength at the aperture and covers two pixels the loss of horizontal displacement has a secondary effect. Wear in the vertical scan mechanism also caused some horizontal displacement.

The vertical scan is more critical since the image formatting circuitry relies on timing to assign values to the pixels in the matrix and any variation in the motor speed, binding of the linkage or flexing of the secondary will result in misalignment of the pixels in the upwardly going columns as compared to the interleaved downwardly going columns. Additionally, any vibration will result in a frame-to-frame misalignment. All of these problems were evident in the original brassboard. Figure 2.2-1 shows the original mechanism.

These problems led to an effect referred to as an image comb since the dark image of a weapon would be displaced up and down on adjacent columns. Since the amount of displacement varied from frame-to-frame the image could not be completely corrected in the display software. The severity of the displacement also varied with the frame rate.

The scanner design was theoretically elegant but not practical with regard to the required tolerances, alignment and expected wear.

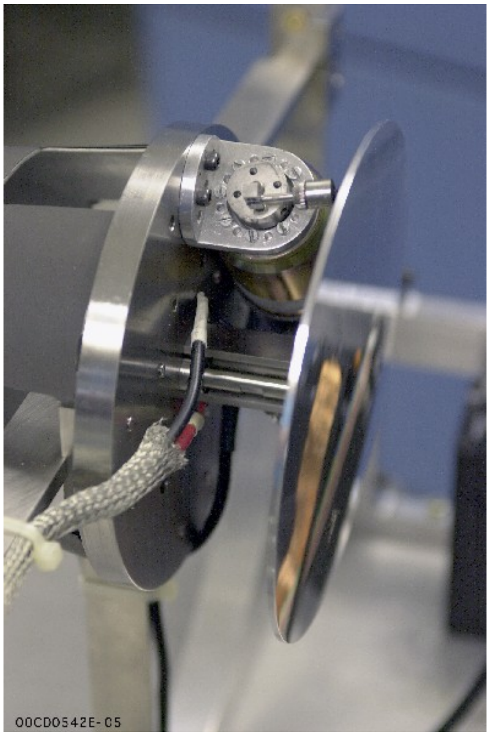

Figure 2.2-1. Micromoe Motor Drives Secondary
(High voltage wires lead to the Piezo electric driver for horizontal displacement)

Some improvement was achieved by mounting the motor square to the direction of travel to minimize twisting of the mirror. This arrangement blocked a small portion of the optic aperture but the loss was more than offset by the smoother operation. Use of a longer lever arm and mounting of the motor on the other side of the plate, as shown in the Figure 2.2-2 design, also provided smoother motion. Increased maintenance by replacing the bushings also reduced the instability and allowed software corrections to be implemented to improve the image.

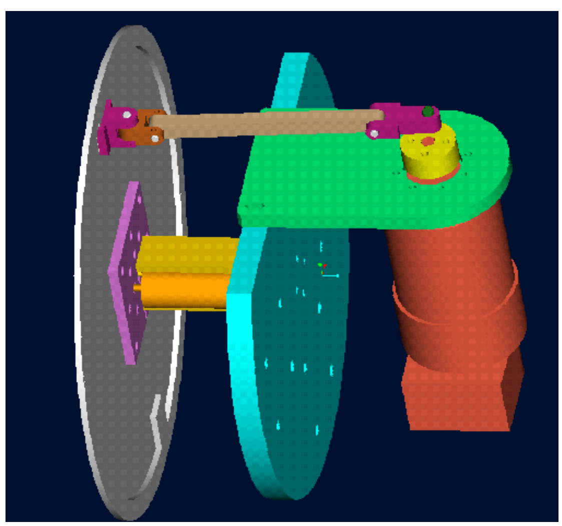

Figure 2.2-2. Scanner redesign included re-location of the motor

Scanners with reciprocating motion might be avoided in favor of scanners with rotational motion. Rotational scanners introduce another set of problems including non-uniformity of dwell time throughout the scene and polarization concerns. Several variations of rotating scanners were considered and an implementation is reserved for the next generation of the hardware.

2.3 Electronics Redesign

Stabilization of the modules improved the operation of the existing electronics and made possible system operation without major modifications. However, the current electronics are not optimized for low cost or for control of the integration time. The latter problem is complex and results in a reduced benefit when running at low frame rates. The more stable modules reduced the need for automated calibration but did not eliminate it.

Circuit modifications were identified to address the above deficiencies. Control of integration time is important to achieve the benefits of reduced frame rate when the operator requires greater sensitivity. The integration interval must be synchronized with the scanning motion so that the samples are taken during the more linear portion of the cycle, associated with the proper pixel and are not taken during the mirror turn-around. Given the erratic motion of the scanner, these conditions could not be met since the synchronization method is based on a time index rather than a true position reading. Position codes available from the drive motor were found to be ineffective since the downstream mechanical irregularities prevented attaining information on the actual position of the secondary mirror. Use of the position codes did compensate for any inconsistency in the motor speed but this was an incomplete solution. Future use of position codes could be effective if the mechanical scanning mechanism is constructed so as to provide a consistent motion of the image over the detector antenna elements.

The ambiguity in the integration implementation caused us to suspend hardware modification plans for the integration circuitry in favor of design activities and selection of more appropriate components. The original boards were constructed with many discrete components and low-level integrated circuits to allow laboratory modifications during system prove-out. Now the emphasis is shifted to production considerations and cost so that selection of more highly integrated specific purpose parts is appropriate.

Parts were selected to meet channel-to-channel consistency goals, eliminate on-board adjustments, and to meet size and cost goals. Although the current boards (Figure 2.3-1) are sufficient for use in the brassboard with the more stable detector modules, they are inappropriate for general field use or production.

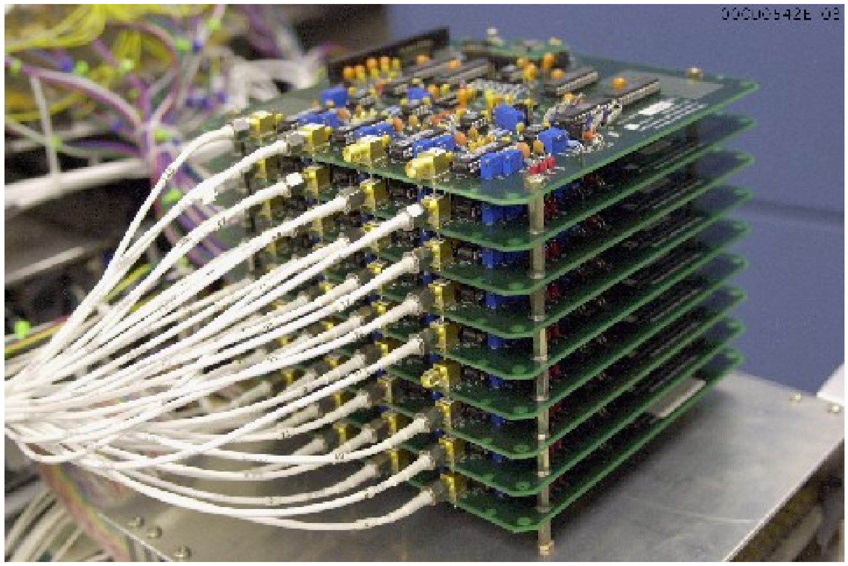

Figure 2.3-1. Original electronics boards were adjusted to operate with rework detectors

2.4 Electronics Assembly and Test

Limited modifications were made to the electronics boards to facilitate calibration adjustments and to match the amplifier gain requirements to the characteristics of the improved detector modules.

More extensive rebuilding of the boards in conformity to the redesign was considered to offer a small payoff given the constraint of the sensitivity limitations in the current detector configuration. The redesign benefits could be fully realized only with multi-channel detectors that integrate the array antenna elements directly with the transition to the MMIC chips and with a scanner that presents a consistently indexed scene. Such a complete rebuild was beyond the scope allowed by the funding. The complete redesign will be appropriate for the next generation of the technology.

2.5 System Integration and Test

The system was populated with the reworked modules and the reworked scanner was installed. The electronics were calibrated to be compatible with the reworked modules and the system was operated to determine the overall performance. Image resolution was initially marginal due to the non-optimized changes in the scanner. Modifications were incorporated in the software to improve the image quality and to provide an effective increase in system sensitivity.

Overall system size was not a parameter for improvement on this contract but is an important consideration for future developments. Figure 2.5-1 shows the laboratory configuration of the brassboard that was optimized for accessibility. An engineering estimate was made of the future size given the use of currently available integrated circuits and multi-channel modules. The diameter of the primary mirror is a controlling dimension so that future systems of this type are expected to approximate a cube, 14 inches on a side, when configured with a 12-inch primary.

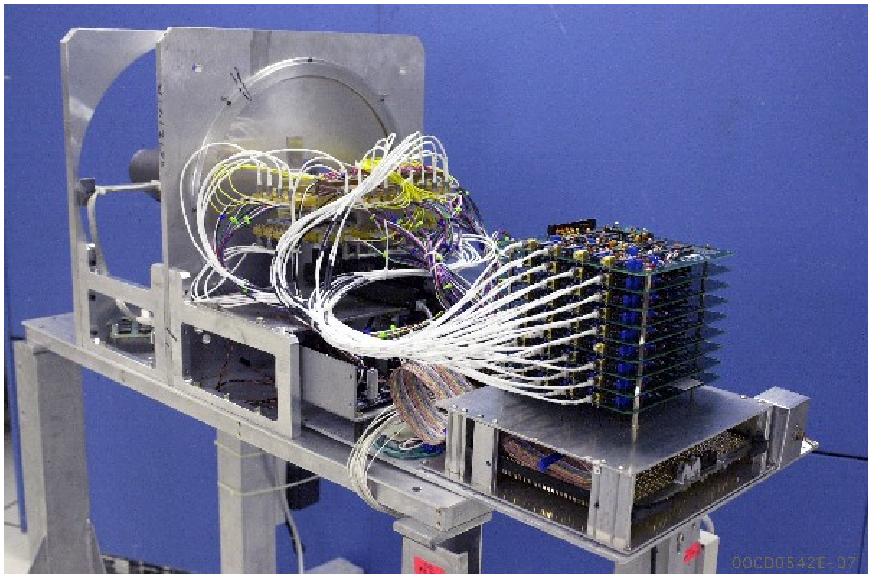

Figure 2.5-1. Brassboard electronics provides opportunity for downsizing

Focusing is accomplished by moving the detector antenna element assembly (Figure 2.5-2) on a linear track. This is an important feature that allows working down to 6 feet where the focus is critical due to the short depth of field. Standoff distances of 20 feet allow focusing with a greater depth of field so that subjects anywhere from 15 to 30 feet have sufficient clarity although the pixel size is greater at longer distances. The focus mechanism is configured with a motorized drive and can also be adjusted manually.

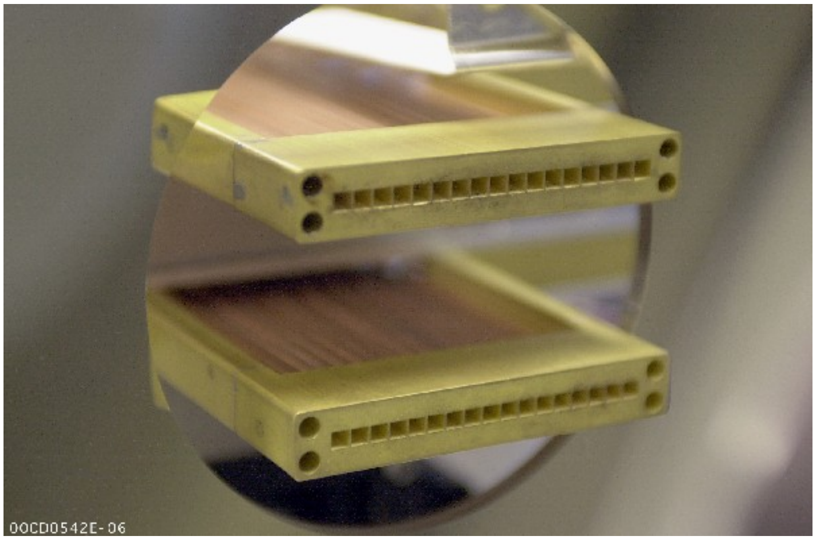

Figure 2.5-2. One by seventeen (1 x 17) horn arrays move on a track to focus

2.6 Sensitivity

A measure of the overall system NEDT was made using hot and cold targets. We did a test to determine the absolute sensitivity of the system. Two bottles of water were placed in front of the camera, one at 50 C and one at 0 C. A 25-frame image sequence was taken and data extracted to determine sensitivity. Sixteen detectors were in the system and vertical scanning produced a 22 by 16 image that was recorded and evaluated with the hot target on the right and then on the left so that data was produced for high and low temperature for each detector. Since a significant factor in the system effectiveness is the determined by fluctuations in the pixels caused by both detector instability and system effects. Measurement of the detector sensitivity in the system as opposed to at the detector level provides a better measure of the system sensitivity.

We now need to know the fluctuations of the pixel output when staring at a constant temperature. A sequence of 25 scans was used to calculate statistics by determining the mean and standard deviation for each pixel (Figure 2.6-1). Since each pixel can be related to a specific detector, we can then group the statistic of many pixels to individual detectors. Even as the observed temperature changes, we are most interested in the standard deviation of each detector.

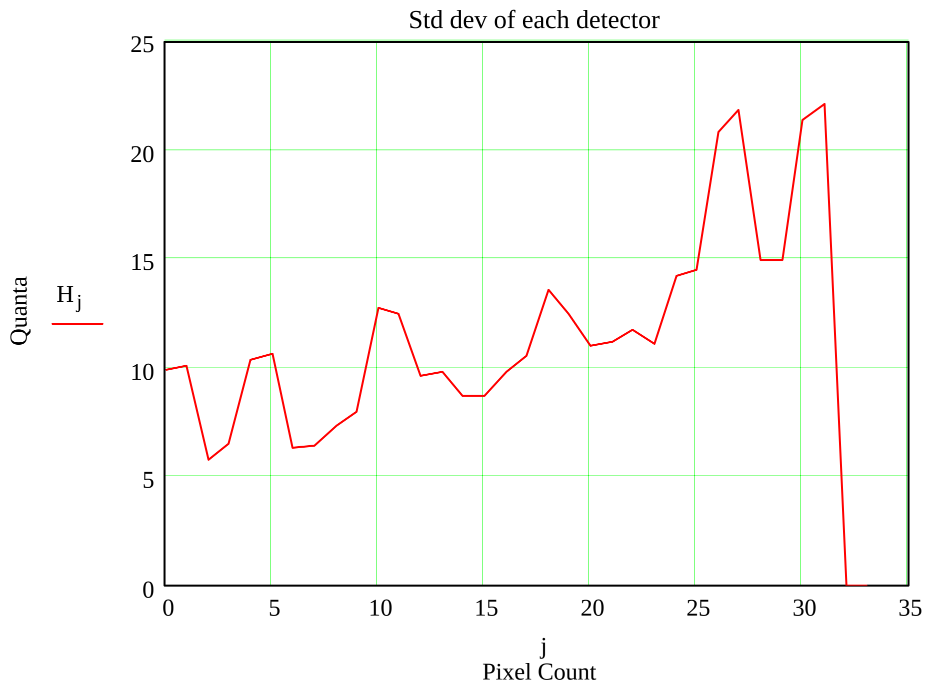

Figure 2.6-1. Standard Deviation

The product of the sensitivity and the fluctuations gives the minimum detectable temperature difference, assuming we can discern a 1-sigma difference.

So our sensitivity varies from 1.7 K to around 5 K for an image look time of 850 µsec, with the better detectors on the left side of the image (Figure 2.6-2). We actually only have 16 detectors in this image, so every even and odd pair are really the same detector (i.e., detector 0 and 1 are the same, 2 and 3 are the same, etc.). As a check, each pair has nearly identical sensitivity, as expected.

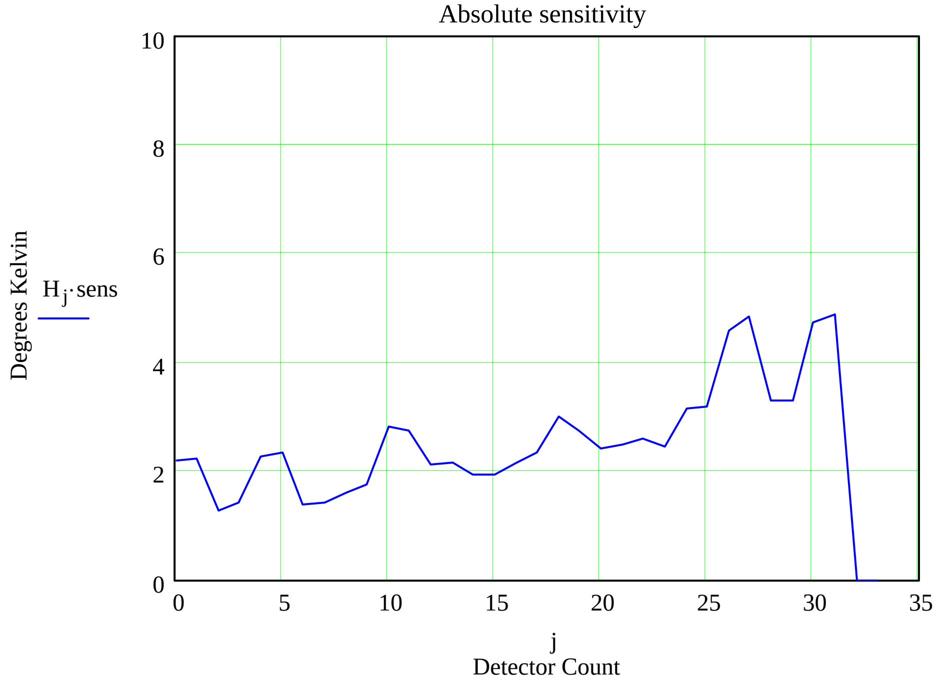

Figure 2.6-2. Absolute Sensitivity

If we normalize this to the sensitivity expected on a single frame-by-frame basis at 15 Hz, it becomes 3 times worse making our best frame-to-frame sensitivity about 5°K. This is consistent with the data taken at the detector module level when accounting for the losses in the particular system application.

3.0 DEMONSTRATION

Testing was performed in accordance with the Test/Demonstration Plan (A003) dated July 2002.

The system was configured with a minimal set of detectors (16) to determine the feasibility of operation with a low- cost system. Subjects were observed at 12 feet for a test of the sensitivity and resolution. Initial operation in the laboratory showed that the sensitivity was still insufficient for practical indoor operation although persons walking through the field of view were detected. In an outdoor situation, the test articles consisting of a simulated (toy) gun and aluminum targets were readily discernable under a medium-weight jacket and behind drywall.

The system was deployed at an entrance where persons ascend a stairway that is at 90 degrees from a landing and walkway leading to the doorway. The partially covered walkway is 25 feet in length with railings completely around. The camera was positioned under the partial roof and the subjects were observed at the top of the stairway as they turned to walk toward the camera. The distance to the subject was 11 to 14 feet so the focus was set at 12 feet.

Environmental conditions during the main demonstration were 85°F, with approximately 80% relative humidity. The test was conducted in the evening so the sun was obscured behind the building or below the horizon. Sky conditions were partially cloudy with cloud bottoms above 15,000 feet and at least 60% open sky.

The system was allowed to stabilize in the outdoor environment and the detectors were adjusted to provide a mid-range gray image in the absence of subjects. A video camera was positioned above the MMW camera to record the scene and the subject. The field of view of the video camera was greater than that of the MMW camera to aid in subject identification by a typical operator.

Images were recorded digitally and are incorporated in the image database (CDRL A004). Video images were also recorded and used to perform side-by-side comparisons for subsequent presentations; these are also in the image database.

The system was operated at 10 Hz with the Dickie circuit set at 10 KHz. Images were recorded and displayed at only 5 Hz due to a software/firmware problem. Provision was also made in the software to perform averaging over 10 frames to smooth the data but this option was not generally selected.

At the beginning of each scene, the weapon was displayed without concealment as a situation calibration. The weapon was then concealed under a medium-weight lined jacket and the subject moved across the scene.

With only 16 detectors operating the effective MMW camera FOV was approximately 8.5-degrees horizontal and 6-degrees vertical (that equates to approximately 21-inches horizontal and 15-inches vertical).

The demonstration was repeated and recorded using a ½-inch thick drywall to conceal the weapon that was hand held. Data were recorded and appear in the image database.

The system-level minimum detectable temperature differential was measured using hot water and ice water targets in the laboratory. The overall system has a useful delta T of approximately 6°K although there is some variation across the image due to residual differences in the detectors. When analyzed on a detector-by-detector basis the best detectors obtained 5°K whereas the worst detectors were nearly 15°K. These calculations are based on operation in the system that includes losses introduced by the horn antenna elements, the waveguide runs and the waveguide to microcircuit transitions. Such detectors can be adjusted to provide reasonable images outdoors in the current system configuration but are not sensitive enough to provide useful images indoors.

4.0 DATA COLLECTION

Images were collected and stored to CD in .avi format. Video recordings were also made so that the scene could be visually synchronized to the radiometer images. The recorded database information is submitted separately as CDRL A004.

Data collection was done outdoors on a second floor balcony so that the only clutter immediately behind the subject was a horizontal railing. Objects on the rooftop at distances greater than 300 feet were not discernable in the image even though they included metal reflective shapes. Sky conditions varied from clear to overcast. In one case, testing occurred immediately before the onset of rain and the system continued to image the weapon until the subject became wet.

Operation in near 100% relative humidity gave the worst results. Evaluation determined that the original LNAs are not passivated in the gate region, which is a problem in our open waveguide system. The loss of gain associated with moisture reaching the gate region will be prevented in future modules by incorporating a seal at the antenna feed and by using passivated chips.

Most data collection was done using a simulated handgun (cap pistol) or small pieces of aluminum. The minimal dimension of the targets was one inch while the major dimension was 5 to 6 inches. At 12 feet the “L” shape was clear in the images. The medium-weight lined jacket worn by the suspect provided some reduction in the ability to detect the weapon but the simple automatic target recognition (ATR) software was able to track the weapon location most of the time. When the L-shape was lost, the ATR occasionally tracked false images caused by glint in the neck area but quickly returned to the weapon as the position changed.

The final review includes side-by-side recordings of the subject and the resulting MMW camera images.

5.0 OBSERVATIONS

The passive millimeter wave camera configured around Cassegrain optics provides a capability for continuous focus at distances beyond 6 feet. Pixel size varies directly as the distance to the target so that a practical maximum working distance for the current system using the 12-inch primary is about 30 feet for detection of handguns. At 12 feet, the pixel size is 2/3 inch so that the shape of even small guns can be resolved. Images obtained at greater distances lose resolution as the object's temperature response covers less than a whole pixel or partially overlaps 2 pixels since the pixel intensity is determined by the average of the energy over the pixel area. Larger items can be imaged at greater distances.

The primary aperture and the wavelength determine the resolution. In our system the blur circle is approximately twice the pixel size. In the static case this causes an object's edge to be ambiguous but when there is some movement of the object the blur circle effect interacts with the pixel size to produce a smoothing effect in the image when displayed at 5 Hz or higher.

Scaling the system up and using more sensors can accomplish operation at longer range. For example, the use of a 4-foot primary antenna would allow operation at standoff distances up to 200 feet. As the distances increase, the depth of field also increases so that the need to refocus as the subject moves is reduced.

The camera was operated at frame rates up to 30 Hz using the scanner. High frame rates reduce the dwell time for detection with a resulting decrease in sensitivity. We found that operation at frame rates as low as 5 Hz can produce usable real-time video images. For manual image viewing, there was little advantage in operation above 15 Hz with regard to producing an image that the human eye-brain combination can follow.

5.1 Remaining Detection Impediments

Detector modules were modified and improved but remain the area of the system hardware with the most potential for additional performance. The waveguide runs shown in Figure 5.1-1 and the associated transitions are a major source of signal loss. Multi-channel modules that would eliminate the waveguide runs and the transitions would save approximately 2 dB in noise figure. Multi-channel modules can be readily fabricated with antenna elements at one-wavelength spacing so that the edge of the module would be positioned in the location now occupied by the 1 by 17 horn array in the focal plane. More advanced modules with a ½ wavelength channel-to-channel spacing would simplify the scanning mechanism.

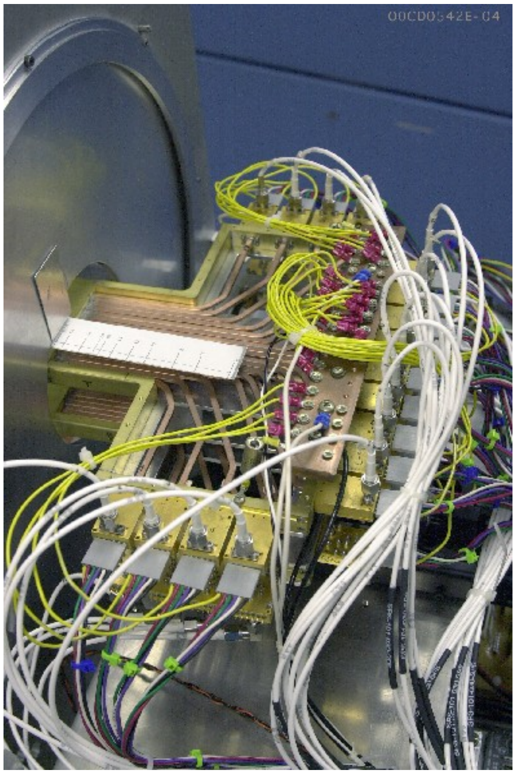

Figure 5.1-1. Waveguide runs prior to detectors introduce approximately 2 dB loss

Mechanical scanning with a reciprocating motion is expensive to implement in a compact form and has the inherent problems associated with wear. A lower maintenance scanner can be designed to reduce both the instability in the image and the off-track scanning due to wear that we see in the current brassboard.

5.2 Detection Enhancements

Images produced for operator decision making can be enhanced by software to reduce noise levels in the image. System noise and individual detector instability affects MMW imagery through uneven intensity, indistinct edges and a speckled appearance. Since noise is random over time, temporal averaging of successive images in a video stream can improve viewing ability. However, this technique requires a high frame rate to prevent blurring caused by moving objects in a scene. The system was operated at 10 Hz with 10 frame temporal averaging. The images were more discernable when the subject was stationary but any movement caused a blur equivalent to that produced with no averaging and a frame rate of 1 Hz.

A second method that effectively reduces noise is the median filter. Median filtering is applied on a per frame basis and thus is not affected by motion in the scene. Since our image is produced by scanning in the vertical direction, there are vertical bands in the image whenever the detectors are not perfectly matched. We saw significant improvement when applying a median filter to compensate for detector differences. Both temporal averaging and median filtering may be used simultaneously.

6.0 RECOMMENDATIONS

The brassboard system demonstrated the application of the system design with ability to quickly focus at various distances. Future detector modules should use multi-channel packaging with integral array antenna elements that allow module placement directly in the focal plane to improve sensitivity. This system configuration has application where the working distance is not fixed, where the size of the camera is important and where system design considerations can be applied to the application scene. Specific follow-on models with improved detectors are recommended for the following applications:

1) Medium to long standoff distance concealed explosive detection.
2) Concealed weapons detection at building portals.

A low-cost version of this technology would have more widespread applications for civilian safety and homeland security. Achievement of low cost is dependent on the ability to significantly lower the cost of the detectors and specifically the LNA chips. Lockheed Martin is developing the capability to obtain low-cost components under a separate initiative.